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A RE-DETERMINATION OF THE TRICHROMATIC COEFFICIENTS OF THE SPECTRAL COLOURS

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ABSTRACT—Using a new trichromatic colorimeter a series of colour matches through the spectrum has been made by ten observers. The results have been averaged and a mean set of trichromatic coefficients for the spectral colours derived. These results are compared with previous determinations made by König and Abney. The variations in the coefficients that have been found amongst the ten observers must, as a consequence of a new method of basing the trichromatic units, be attributed to variations in the process of reception, but their magnitude appears to be of a small order. On the other hand, there are big differences in the amount of the macular pigment in different eyes and probably some variation in its dominant hue. These variations have been investigated by matches on a standard white, results for 36 observers being given in the paper and a mean value determined. This value, combined with the mean spectral coefficients, has been used to compute an average locus for the spectral colours in the colour triangle, with white at the centre.

Other points discussed in the paper include the technique of colour matching, the range of intensity over which matches remained valid, and variations of luminosity.

INTRODUCTION

In a previous paper* a colorimeter was described which had been designed and built by the author to carry out some researches on colour vision in the Technical Optics Department of the Imperial College. The present paper describes the first results that have been obtained from observations made by a number of observers, all trichromats. The main results are concerned with the determination of the trichromatic coefficients of the spectral colours, that is to say, the proportions of

* W. D. Wright, "A Trichromatic Colorimeter with Spectral Primaries," *Trans. Opt. Soc.* 29 1927-8 (225).

three selected primaries, red, green, and blue, which are required to match the colours ranging through the spectrum. These values determine the positions of the spectral colours in the colour triangle and when combined with relevant luminosity data they may be used to compute the spectral mixtures curves and the sensation curves. A set of sensation curves has been derived, but they are provisional only, as satisfactory luminosity values are not yet available.

The value of the results is two-fold: first, in the realms of physiology the information is fundamental to the study of colour vision and must underlie and be explained by any theories dealing with the subject; secondly, the science of colour-measurement or colorimetry depends for its basic principles on the colour triangle, the locus of the spectral colours in that triangle, and on the sensation curves. This is the ground that is being covered by the research.

The figures at present available in this field have been derived from experiments made either by König and Dieterici or by Abney. Both sets of results have been criticised on technical grounds, and the paucity in the number of observers has further diminished their value. Attention may be called to a paper by Guild* and a monograph by Troland†, both of whom refer to the urgent need for the accurate re-determination of the three-colour mixture data.

THEORETICAL CONSIDERATIONS

As the customary method of calculating the results has not been followed, it will be necessary to outline in brief the theoretical side of the problem. It is an experimental fact that, with some few exceptions, any colour can be matched by a mixture of three colours, which we call the primaries. Or, making no exceptions, every colour can be uniquely represented by an equation of the type

$$C = \alpha R + \beta G + \gamma B$$

where α , β , and γ are coefficients, positive or negative, representing certain proportions of the red, green, and blue primaries respectively. If α , β , and γ are all increased in the same ratio, the colour represented by the equation will not have changed in quality, but there will simply be more of it, that is, its intensity is increased. It is therefore quite legitimate and involves no loss of generality, if we arbitrarily decide to make $\alpha + \beta + \gamma = 1$. This restriction, in effect, separates the two variables, luminosity and colour, so that each can be dealt with individually. When the coefficients add up to unity the colour equation is referred to as a unit trichromatic equation and the amount of colour represented by the equation is one trichromatic unit (one T. unit). The conception of such a unit is extremely useful. It fulfils the ordinary arithmetical laws; for example, if we mix one T. unit of a colour C_1 with one T. unit of another colour C_2 , then we have 2 T. units of some

* J. Guild, "A Critical Survey of Modern Developments in the Theory and Technique of Colorimetry and Allied Sciences," *Proc. Opt. Convention*, 1926 (61).

† L. T. Troland, "The Present Status of Visual Science," *Washington Nat. Acad. of Science, Bull. Nat. Res. Council*, vol. 5, Part 2, No. 27, 1922.

third colour C_3 and so on. The elaboration of this process is clearly explained in a paper by Guild*.

To determine the units of the primaries it is customary to match white by a mixture of the three primaries of the colorimeter in use and to correct the readings as given on the instrument scale by suitable factors, so that for this match all three shall be equal. These factors are then applied throughout any series of matches. This method has some underlying theoretical justification, since it may be considered that the proportions of the white match have equal colouring values as, when mixed, they produce a colourless sensation. But, in practice, it is really immaterial on what basis the units are founded, so long as they are consistent throughout.

A simple example of the method may be useful. Suppose that the intensities of the primaries in the colorimeter are controlled by variation of sector openings and that these angular apertures for the white match are 30° for red, 15° for green, and 60° for blue. To correct these readings so that they are in equal proportions, a factor of 2 must be applied to the red and 4 to the green and these factors must be used in any subsequent colour match. Thus, if for a new colour the instrument readings are 40° for red, 10° for green, and 20° for blue, the proportions, in the units agreed upon, are

$$\text{red } 80 \quad \text{green } 40 \quad \text{blue } 20$$

giving the trichromatic coefficients as

$$\text{red } 80/140 = \cdot 571, \quad \text{green } 40/140 = \cdot 286, \quad \text{blue } 20/140 = \cdot 143$$

from which we have the unit equation for the colour as

$$C = \cdot 571R + \cdot 286G + \cdot 143B.$$

The function of the white match in this example has been to provide two factors, one for the red readings and another for the green. Any other basis by which two such factors can be determined will be equally valid and provide an equally consistent series of results. Suppose, for instance, that we match a monochromatic orange plus the necessary small amount of desaturating blue and that the sector readings are 10° for red, 30° for green, and 6° for blue. We can agree to make the amounts of red and green in this match equal, so providing a factor 3 for the red. In the same way we can match a monochromatic blue-green, desaturated in this case with sufficient of the red primary for it to be matched, the instrument now reading, say, 3° for red, 30° for green, and 15° for blue. From this match we obtain a factor 2 for the blue, if we agree to call the amounts of green and blue in this colour equal. Applying these two factors to all future matches we obtain a series of results on a system as consistent as before and one that can be compared with the first by suitable mathematical transformations. The advantage of basing the units on matches of monochromatic colours becomes evident when we have to compare the results for two or more observers.

* J. Guild, "The Geometrical Solution of Colour Mixture Problems," *Trans. Opt. Soc.* **26** 1924-5 (139.)

Consider the case of an observer who has matched white and based his units on that match and has then made a series of matches to determine the coefficients of a number of the spectral colours. These can be plotted in the colour triangle with white at the centre. (The properties of the colour triangle are fully described in the paper by Guild quoted previously.) Now consider the effect of a yellow filter placed in front of the observer's eye if he repeats his observations, again basing his units on a match with white. The quality of the white will be affected by the filter, becoming a more or less saturated yellow according to the filter used, but the quality of the spectral colours will remain unchanged since they are monochromatic radiations. Thus the relation between the white and the spectral colours cannot remain the same as in the first series of observations; therefore, since the white will again be plotted in the same position as before, that is, at the centre of the triangle, it follows that the spectral colours will have a new locus.

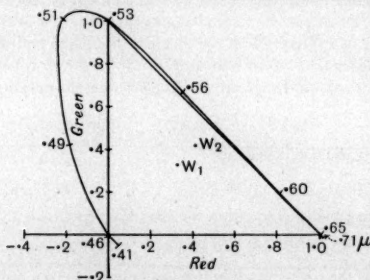


Fig. 1

If, however, the same two sets of observations are worked out by basing the units on matches with two monochromatic radiations, as suggested above, the position becomes reversed. Since the quality of neither the spectral colours nor the "unit-colours" is affected by the yellow filter, their relative positions in the colour triangle will be unchanged, with the result that the spectral locus will be the same in both cases. As the white, on the other hand, is modified by the filter, it will take up a new position in the triangle. The effect is shown in Fig. 1, where the continuous curve represents the spectral locus in the colour triangle, and W_1 and W_2 are the positions of the white point without and with the filter respectively. The distance between W_1 and W_2 is a measure of the yellowness, or saturation, of the filter and, for varying degrees of saturation, the locus of W_2 will be a straight line passing through W_1 . The intersection of this line with the spectral locus gives the dominant hue of the filter. These pieces of information can be immediately deduced from the results, provided they are expressed in units based on spectral colours; on the white basis the facts are indicated by a general shift of the spectral locus, which illustrates the true state of affairs in a very indirect and obscure fashion.

The value of this discussion for comparing the results of several observers becomes apparent when we consider the constitution of the human eye. Between the cornea of the eye and the retina there exist a number of absorbent materials the most potent of which is the macula lutea, a yellow pigment of quite small extent, generally just exceeding the fovea centralis in area. Whilst the other absorbent materials are relatively transparent and unlikely to vary to any great extent from one person to another, the yellow pigment may have a very pronounced colour and may vary greatly in amount amongst different observers. Thus, although there may be variations in the receptor processes in the eye and in the nervous conductions to the brain, these cannot be investigated until the variations in the macular pigment are first isolated. This can be done by working with units on a spectral basis, for any variation in the density of the pigment will then show itself by a variation in the position of the white point in the colour triangle along a straight line. A position off this line may indicate a variation in dominant hue of the pigment, whilst differences in the coefficients of the spectral colours will imply variations in the physiological processes of reception and perception. However, although a variation in dominant hue may be indicated by the results, it does not necessarily follow that such variation is the result of a change in the constitution of the pigment, for it is possible that an increase in the density or the thickness of the pigment would produce a change in its dominant hue as well as in its saturation. This phenomenon does occur with some coloured liquids, but from the character of its absorption curve it appears probable that in the case of the macular pigment the effect, if any, would be small.

THE EXPERIMENTAL ARRANGEMENTS

For a description of the apparatus used, reference should be made to the paper by the author already quoted in the introduction. In using the instrument two persons are required, one for observing and the other for noting down the readings when matches have been made. The second experimenter is also responsible for setting new colours to be matched and for making any other experimental adjustments that may be required. The observer is thus solely concerned with colour matching, a fact that tends to create the right mental atmosphere, an important consideration in work such as this, in which the temperament of the observer plays a big part in the accuracy and reliability of his observations. Whilst no indication was obtained that the state of adaptation of the observer affected any match, it was thought desirable to allow the observer five or ten minutes' dark adaptation before commencing a series of observations; this at any rate gave time for the observer to settle down and for after-images to disperse to some extent.

The mean wavelengths of the primaries used in the experiments (spectral primaries are employed in the instrument) were $\cdot 650$, $\cdot 530$, and $\cdot 460 \mu$. The choice was an entirely practical one, the deciding factors being a desire to make the negative coefficients as small as possible and to have sufficient intensity of the blue primary. The results can, however, be transformed to any other set of primaries that may be

desired, provided their position in the colour triangle is known. The widths of spectrum included in the pencils of light reaching the eye were 0.060μ for the red primary, 0.035μ in the green, and 0.016μ in the blue. The corresponding width of any other part of the spectrum can be approximately interpolated from these figures. Whilst, with this relatively big range of wavelength, the beams cannot be considered strictly monochromatic, it is apparent that the colour of the integral light cannot differ greatly from the colour corresponding to the mean wavelength of the beam, since the light in the two halves of the band will mix to give a colour very nearly the same as that of the central pencil. A rough calculation based on the sensation curves for white light showed that the correction required amounted to about 0.002μ , even in the part of the spectrum of greatest hue sensitivity (about 0.580μ). Any error introduced from this cause can, therefore, be safely neglected, since even in this region the hue sensitivity is only about 0.010μ .

A square field of view, divided horizontally into two equal rectangles, has been used, the whole subtending approximately 2° at the eye. This ensures that the fovea alone is involved in the colour matching and so avoids complications which might arise from the varying structure of the retina; it further ensures that, in general, the image falls entirely within the bounds of the yellow spot. A 2° field is in line with the standard suggested by Guild and with the standard used in flicker photometry. The effect of a light surround field, as used in flicker photometry, was also investigated, a surround field of about 10° angular subtense being provided.

As it was much to be desired that some luminosity measurements should be made in the course of the work, a form of flicker photometer was set up, by means of which the relative intensities of the three primaries could be measured. The arrangement consisted simply of an illuminated white sector which rotated so that the primary and the rotating sector came into view alternately. When the correct speed of rotation was obtained, the sensation of flicker could just be made to disappear by suitably varying the intensity of the primary. Repetition of the experiment for all three primaries gave their relative intensities. Further, by measuring the intensity of the illumination on the sector with a holophane lumeter, the approximate brightness level at which matches were being made was determined. Allowance had to be made here for the size of exit pupil used in the colorimeter.

To investigate the variation in a colour match, if any, with change of intensity level, a method was used in which a sector rotated so as to intersect both halves of the field. In this way the intensity of the two fields was reduced equally.

The white to which the results relate had an energy distribution similar to that of a black body radiating at 5000°K .^{*} This was obtained with a 1000-watt lamp standardised at the National Physical Laboratory, the light from which, after passing through a standard liquid filter, fell on a white magnesium oxide screen.

THE TECHNIQUE OF COLOUR MATCHING

One or two notes on the technique adopted in making the observations may be usefully inserted here. In making the first match of a colour, practice and experience seem to be essential to attaining the desired result in a reasonable time.

^{*} See Appendix, p. 158.

It was found impossible to formulate satisfactory rules for the guidance of fresh observers and the difficulty in such cases was largely overcome by a more practised observer making a rough match first. In repeating a match (each colour was matched three times to obtain a mean result) it is only necessary to upset it sufficiently for the match to be perceptibly wrong; to do more than this is a waste of time without any compensating gain in accuracy. Moreover, provided the first match is a reasonably good one, it is easier and appears legitimate to upset and readjust one primary at a time. This not only saves time, but also simplifies matters for the observer and so decreases the mental strain involved. If it is found that a good match cannot be made without adjusting all three primaries together, such an adjustment can always be made. A precaution, which probably prevented a number of bad matches being passed off as satisfactory, consisted in asking the observer to look away from the field of view for a few seconds when he thought he had made a match and then, after a short rest, to see if he was still satisfied with the match. The general practice of occasionally looking away for a second or two rather than steadfastly staring at the field is to be recommended for comfortable and accurate work. The time which is taken over a match depends largely on the temperament of the observer and the amount of practice he has had. It is best if possible to strike a happy mean between rapidity and care. Neither the very rapid nor the over-conscientious type of observer is likely to make consistent settings and the latter is bound to suffer from exhaustion in a short time. With practice it should usually be possible to make a satisfactory match in about a minute or a minute and a half.

THE RESULTS

Coefficient curves for the spectrum have been obtained for ten trichromats in all, each observer making about thirty matches through the spectrum. In order to determine the average values it was found more convenient to plot the coefficients for each primary against the wavelength of the spectral colours as a separate curve than to represent each colour as a point in the colour triangle. The difficulty, if this were done, arises in determining the mean curve; for not only has the average shape to be found, but the wavelength scales on the spectral loci must also be averaged. This complication can be overcome by plotting the coefficient curves separately.

In Fig. 2 the ten sets of results obtained are shown superposed; the coefficients are plotted as ordinates against a horizontal wavelength scale*. The wavelength of each primary is given by the point where its own curve has the value unity and the other two curves are zero, whilst the points at which the red and green curves and the green and blue curves intersect, namely at S_1 and S_2 , indicate the two spectral colours, of wavelengths 5825 and 4940μ , on which the units were based.

In addition to obtaining a mean set of curves from Fig. 2, the significance of the variations that occur between different sets needs to be investigated. In this connection it must be borne in mind that each set of curves must necessarily be

* It should be noted that in Figs. 2, 3, 4, and 5 the wavelength scale is not uniform, having been directly transposed from an arbitrary instrumental scale.

somewhat similar in shape by reason of the fixed points through which all the curves must pass. Thus the variations that occur may be of greater importance than would at first sight appear probable.

The part played by observational and instrumental errors in producing the differences has first to be discussed. Generally, the observers were new to the art of three-colour matching, but in all cases some time was spent on practice observations. The settings of the more accurate observers could usually be guaranteed to within 1 or 2 per cent. for the red or green primaries and 3 or 4 per cent. for the blue primary, provided the amount of the primary required in the match

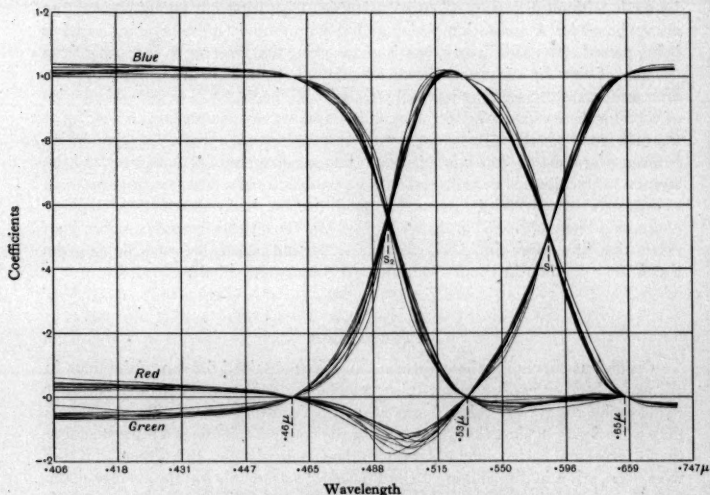


Fig. 2. Superposed coefficient curves of 10 observers

was reasonably high. The effect of these percentage errors on the derived trichromatic coefficients can be very easily determined for a given case and this is the only safe course to adopt. It is impossible to lay down general estimates of the reliability of the coefficients, quite apart from the variation of hue sensitivity over the colour field.

The chief sources of instrumental error are three in number: the inaccuracy of the wedges and their calibration; error of wavelength setting and calibration; and change in the colour temperature of the pointolite lamp. The first of these was reduced to a minimum by frequent calibration of the wedges; the second was almost certainly negligible since the wavelength scale was checked as a matter of

routine with a mercury lamp before any series of results was attempted; whilst the possibility of the third was rendered remote by running the lamp off the batteries instead of the mains and by introducing a voltmeter and variable resistance into the circuit. The magnitude of the first source of error, namely that of the wedges, is the only one that need be seriously considered. The intensity of light transmitted could be measured to an accuracy of about 1 or $1\frac{1}{2}$ per cent. with the wedges that were in use. This is an error larger than one would wish, as it is of almost the same magnitude as the observational error of an experienced observer, but, in view of the big differences in matches made by different observers, its ultimate significance is small.

Considering now a concrete case, it is possible that between $\cdot 65$ and $\cdot 53 \mu$ the blue, which is only present in the match in small quantities, may be determined only to within 20 per cent. of its true value. If we take the coefficients of S_1 as

$\cdot 507$ red $\cdot 507$ green $-\cdot 015$ blue,

then a 20 per cent. change in the blue gives the new coefficients as

$\cdot 509$ red $\cdot 509$ green $-\cdot 018$ blue.

Again, between $\cdot 53$ and $\cdot 46 \mu$, the red may be matched to within 10 per cent. An error of this magnitude on the coefficients of S_2 , which we may take as

$-\cdot 130$ red $\cdot 565$ green $\cdot 565$ blue,

will give a new value of

$-\cdot 144$ red $\cdot 572$ green $\cdot 572$ blue.

Judging from these figures it appears that the variations that occur between $\cdot 65$ and $\cdot 53 \mu$ cannot be explained as observational errors. I am inclined to think, in fact, that there are genuine differences in the amount of blue required in the matches, but the question is a very open one. Over the blue-green portion of the spectrum the variations appear still more marked and cannot, I think, be wholly due to observational error, despite the fact that the observations were generally remarked upon as being more difficult in this region than elsewhere. The evidence for actual variation in the receptor or more central processes certainly appears strongest here. Variation in macular or any other pigment is, of course, eliminated by the system of units used. From the blue primary to the end of the spectrum the variations are surprisingly small and of no great significance.

The mean set of curves obtained from Fig. 2 is shown in Fig. 3. Of the qualitative features of these curves, the rather sudden bend in the negative portion of the red curve is of interest and the position of this minimum may have some significance. Any physical or physiological interpretation of such features is, however, hardly likely to be obtained until the data are converted into terms of "sensations." The method of representing the results that is used here is useful for practical purposes, but of no special value theoretically.

In Figs. 4 and 5 the results obtained by König and by Abney are shown; their results have been re-calculated for the same primaries and on the same unit-basis, so that they are directly comparable. The possibility of doing this further illustrates

the value of the new method of calculating the coefficients, for the specification of the white used was not known in either case. The general agreement of the curves with each other and with Fig. 3 is remarkable: some difference is shown

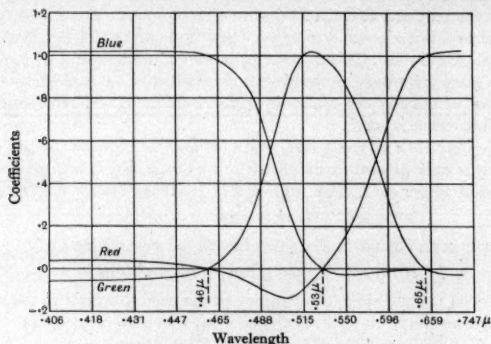


Fig. 3. Mean coefficient curves from results of 10 observers

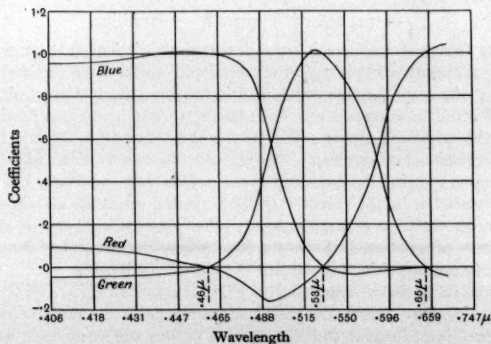


Fig. 4. Coefficient curves re-calculated from König's results

in the dip in the red curve, and the violet coefficients are definitely at variance. Some such variations were anticipated, as low intensity and stray light were bound to affect both Abney's and König's work, especially at the shorter wavelengths.

The data of Fig. 3 are represented in Fig. 6 by the curve lying outside the colour triangle. This is the spectral locus, the scale marked out along the line giving the

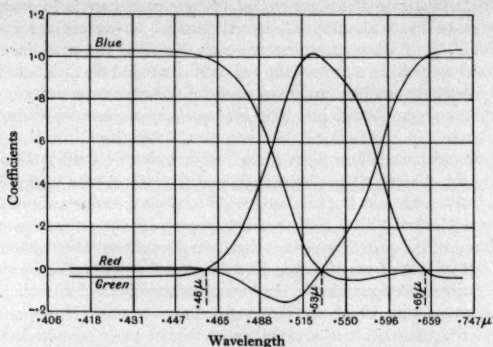


Fig. 5. Coefficient curves re-calculated from Abney's results

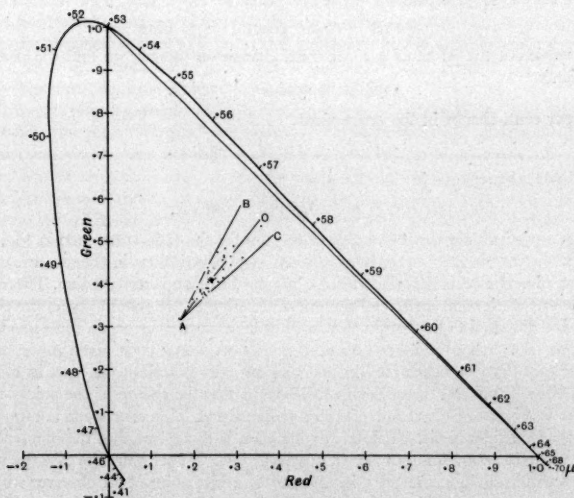


Fig. 6. Colour triangle showing mean spectral locus of 10 observers and white-points of 36 observers

wavelength in microns. The right-angled triangle used here is in practice more satisfactory than the customary equilateral triangle, as rectangular co-ordinates can be utilised. Such an arrangement has been discussed and used before by Ives and Guild. The abscissae represent the red coefficients and the ordinates the green, whilst the values for the blue are given as the differences from unity of the sums of the red and green coefficients. The blue primary is thus represented by the origin.

Inside the triangle I have plotted the "white-points" of thirty-six observers. In all, forty-six observers have been examined, but the results of ten have been discarded, three of them being in some way anomalous and seven showing marked inaccuracy and unreliability. Before the scattering of the points is interpreted, the magnitude of the probable observational error must be investigated.

The effect of lack of practice was diminished as far as possible by making use of the precautions mentioned in the section on the technique of matching. Judging from the accuracy with which the observations were repeated, it appears that the red and green coefficients can be relied on to within 4 per cent. and the blue to within 8 per cent. This estimate is on the safe side, but, even assuming these figures, the effect on the coefficients is not great. If we take as an average for the white coefficients the values

·250 red ·400 green ·350 blue

and work out the effect of a 4 per cent. change on the red we find the new coefficients

·258 R ·396 G ·346 B.

A 4 per cent. change in the green gives

·246 R ·410 G ·344 B.

An 8 per cent. change in the blue gives

·243 R ·389 G ·368 B.

These variations are small and cannot account for the differences seen in Fig. 6.

In the theoretical section it was shown that, if variations in the amount of the yellow pigment occurred, the white points would lie on a straight line. Therefore, if amount of pigment were the sole source of variation, we should expect the points we have obtained to lie, within the limits of experimental error, on some mean line such as *AO*. From the investigation of the observational error given above, added to the fact that the inaccuracy in the blue can play practically no part in making the points lie off *AO*, there seems little doubt that the failure of the points to lie on the line is the result of some further phenomenon. This conclusion is supported by other considerations. A simple explanation is to assume that the pigment not only varies in saturation, but also in dominant hue. If such were the case the white points would lie in a cone with its apex at the white point of an observer with no pigment, and to test this theory the radial lines *AB* and *AC* have been added to Fig. 6, *A* being taken as the "no-pigment" point. The position of this point is confirmed by some extra-foveal observations that were made. The grouping of the

points undoubtedly suggests a conical arrangement, for the scattering at the upper end is much greater than at the lower, in spite of the fact that there are considerably more points in the narrower than in the wider part. If the scattering were accidental, if, for example, it were due to observational error, then the scattering should be greatest where the observations are most numerous. Such, however, is not the case. The conclusion has thus been reached, and is put forward here, that the major source of variation among normal trichromats is due to the macular pigment varying greatly in density and to a less extent in dominant hue. It may be further remarked that the variations represented in Fig. 6 are not insignificant quantities, but are surprisingly big. They must, in fact, seriously affect any system of colour measurement which does not make allowance for such differences.

Attention has frequently been drawn, notably by Maxwell, Helmholtz, König, and v. Kries, to the effect that the yellow pigment must have on colour matching, but the subject has generally been dealt with in a qualitative manner, with little indication how colour measurements were affected. More recently, R. H. Sinden* has discussed the problem from a consideration of complementary colours. He also concluded that the pigment was responsible for the main differences found and showed how, for the eight observers he examined, their "white points" lay approximately on a straight line when plotted in the colour triangle. Sachs† made a post-mortem examination of the pigments of nine human eyes and the absorption curves he obtained appear to support the possibility of a change in dominant hue as well as in saturation. Variation of hue would also explain many of the so-called anomalous matches made on the Nagel anomaloscope.

From the points plotted in Fig. 6, a point in a mean position has been selected to provide data for a "normal" eye. Clearly, the number of observations obtained, whilst considerable, was not sufficient to warrant the determination of the mean by any statistical method such as a frequency curve. The method of determination was therefore as follows. *AO* was drawn so that an equal number of points lay on either side of it; the position along that line was then found at which there were about an equal number of points above and below it. The coefficients for the point fixed in this way and marked with a small cross in Fig. 6 were

·243 red ·410 green ·347 blue.

Having regard to the end to which it is hoped this work, when combined with results of a similar nature obtained by other workers, will lead, namely, to the standardisation of a "normal" eye for colour matching, when this stage is reached it will be theoretically immaterial whether the units are based on a white match or on matches with two spectral colours. For, since only those observers who are normal, or groups of observers whose mean is normal, will be of use in colour measurement, individual variations will not enter into the problem and the particular advantage of the spectral method in demonstrating such variations in a simple manner will no longer be called for. Further, in many cases it will be more

* R. H. Sinden, "Studies based on the Spectral Complementaries," *J.O.S.A.* 7 1923 (1123).

† M. Sachs, "Ueber die spezifische Lichtabsorption des gelben Fleckes der Netzhaut," *Archiv f. d. ges. Physiologie*, 50 1891 (574).

practicable to match the standard white than spectral colours and in any case this involves only one match instead of two. For these reasons the coefficients for the spectral colours have been re-calculated so that the mean white occurs at the mid-point of the colour triangle. The results expressed in this form are given in Table I and Fig. 7.

Table I

Wavelength (μ)	Trichromatic coefficients		
	Red ($\cdot 65\mu$)	Green ($\cdot 53\mu$)	Blue ($\cdot 46\mu$)
$\cdot 41$	$\cdot 051$	$-\cdot 047$	$\cdot 996$
$\cdot 43$	$\cdot 045$	$-\cdot 043$	$\cdot 998$
$\cdot 45$	$\cdot 021$	$-\cdot 024$	$1\cdot 003$
$\cdot 46$	$\cdot 000$	$\cdot 000$	$1\cdot 000$
$\cdot 47$	$-\cdot 031$	$\cdot 057$	$\cdot 974$
$\cdot 48$	$-\cdot 004$	$\cdot 182$	$\cdot 912$
$\cdot 49$	$-\cdot 170$	$\cdot 420$	$\cdot 750$
$\cdot 50$	$-\cdot 233$	$\cdot 772$	$\cdot 461$
$\cdot 51$	$-\cdot 207$	$1\cdot 002$	$\cdot 205$
$\cdot 52$	$-\cdot 111$	$1\cdot 049$	$\cdot 062$
$\cdot 53$	$\cdot 000$	$1\cdot 000$	$\cdot 000$
$\cdot 54$	$\cdot 123$	$\cdot 901$	$-\cdot 024$
$\cdot 55$	$\cdot 232$	$\cdot 797$	$-\cdot 029$
$\cdot 56$	$\cdot 354$	$\cdot 676$	$-\cdot 030$
$\cdot 57$	$\cdot 480$	$\cdot 543$	$-\cdot 023$
$\cdot 58$	$\cdot 604$	$\cdot 414$	$-\cdot 018$
$\cdot 59$	$\cdot 720$	$\cdot 290$	$-\cdot 010$
$\cdot 60$	$\cdot 811$	$\cdot 196$	$-\cdot 007$
$\cdot 61$	$\cdot 881$	$\cdot 124$	$-\cdot 005$
$\cdot 62$	$\cdot 929$	$\cdot 075$	$-\cdot 004$
$\cdot 63$	$\cdot 966$	$\cdot 037$	$-\cdot 003$
$\cdot 64$	$\cdot 988$	$\cdot 014$	$-\cdot 002$
$\cdot 65$	$1\cdot 000$	$\cdot 000$	$\cdot 000$
$\cdot 68$	$1\cdot 011$	$-\cdot 011$	—
$\cdot 70$	$1\cdot 015$	$-\cdot 015$	—
Standard white (5000° K.)	$\cdot 333$	$\cdot 333$	$\cdot 333$
König's white	$\cdot 301$	$\cdot 278$	$\cdot 421$
Abney's white	$\cdot 429$	$\cdot 337$	$\cdot 234$

It was seen in Figs. 3, 4, and 5 how the coefficient curves of König and Abney were in very fair agreement with the present results. In Fig. 7 the positions of König's and Abney's white points are shown, the new coefficients being calculated from their positions in their own triangles by suitable arithmetical transformations; they are seen to differ widely from each other and from the mean point just determined. This explains the apparent disagreement that existed between the two sets of coefficients when based on their white matches.

If we neglect the minor variations that were found in the coefficient curves, then, to determine whether an observer has a normal colour matching eye, matches on white and two spectral colours would have to be made. It must be realised that a person with a normal luminosity curve will not necessarily be normal in colour matching, nor will an observer with an abnormal luminosity curve necessarily be

abnormal in colour matching. For, taking the second case first, an observer may be abnormal as regards luminosity through one of his primary sensations being reduced and yet have a normal amount of pigment. In such a case he will be normal in colour matching, since a diminution in one of the primary sensations does not, apart from reducing the sensitivity of an observer, affect his colour matching. On the other hand a person might have a normal luminosity curve but an abnormal amount of pigment, for the effect of the latter on his luminosity curve could conceivably be neutralised by his sensations being suitably modified. From this we can conclude that the standard luminosity curve has not indirectly standardised the normal amount of pigment and thence the normal colour matching eye. This conclusion is in no sense an idle one, for it would be somewhat of a paradox if two "normal" eyes existed.

Whilst discussing questions of luminosity, it may be worth while to give the results of a few measurements that were made to investigate luminosity variations

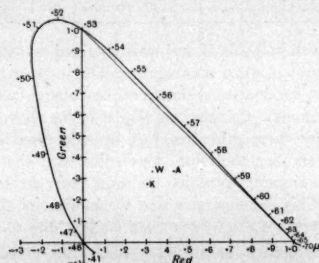


Fig. 7. Locus of spectral colours in colour triangle, with mean white at centre.
W, Standard white (5000° K.); K, König's white; A, Abney's white

amongst different observers. The results differ from other measures that have been made before in that they rule out the effect of the yellow pigment. The method by which this was attained consisted in determining the relative luminosities of the amounts of the primaries required in the matches on the two standard spectral colours, and can best be demonstrated by an example. Suppose that an observer matched one of the standard spectral colours, say the blue-green, and that the amounts of green and blue required were 12 and 18 respectively, as measured on the arbitrary colorimeter scale. Now suppose that in the luminosity measurements 4 units of green matched 20 units of blue; then, measured in luminosity units, the proportions of green and blue in the blue-green match become 60 : 18. Suppose, now, that the observer had his yellow pigment increased and that this had the effect of diminishing the transmission of the green by a factor a and the blue by a factor b . The proportions of green and blue now required in the colour match will be $12/a$ and $18/b$ measured in the arbitrary instrument units, and in the luminosity match $4/a$ units of green will be required to match $20/b$ units of blue.

Then in luminosity units the proportions of green and blue in the match are still given as 60 : 18. Thus, luminosity measures made in this way will be unaffected by pigment differences and variations found must be due to physiological differences in the process of reception, presumably to be attributed to modifications in the sensation curves.

Table II

Observer	Relative luminosity of primaries		
	Red	Green	Blue
<i>A</i>	57.2	100.0	6.5
<i>B</i>	70.8	100.0	4.8
<i>C</i>	58.8	100.0	6.0
<i>D</i>	56.8	100.0	4.6
<i>E</i>	84.1	100.0	4.6
<i>F</i>	73.6	100.0	4.7
<i>G</i>	64.8	100.0	5.1

The results are given in Table II and were obtained by making colour matches of a monochromatic orange and a monochromatic blue-green; the three primaries were then matched in luminosity against a white rotating sector (see section on experimental arrangements). Calculations similar to the above then gave the relative luminosities of the three primaries, but, in order that the results might be comparable with one another, the values were adjusted so that the value for green was always 100.0. The amounts by which the results vary are seen to be very great, particularly for red. This demonstrates that the luminosity differences that have been found before were not solely, nor even largely, due to pigment variations.

With regard to the experimental arrangements for the luminosity matches, these were not carried out under strictly standard conditions. The field size was correct and an illuminated surround was used, but the intensity level of the matches was low. The illumination on the retina, in fact, was of the order of 10 photons only, instead of 120 as is recommended. Further, no observer known to have a normal luminosity curve was available. These results cannot, therefore, be correctly correlated with standard luminosity data, but for comparison amongst themselves they supply the necessary information. Incidentally, if the reasoning given above relative to the normal amount of pigment and the normal luminosity curve is correct, it follows that the luminosity curve has standardised the combined effects of the true relative luminosities of the spectral colours and the absorption factors due to the pigment, without standardising either set of values separately. Thus results such as those given in Table II, which express absolute luminosities, cannot at present be obtained for a standard eye, simply because there is no true luminosity standard. This fact is of no consequence in ordinary intensity measurements, but it is likely to cause considerable difficulty when the problem of standardising the sensation curves arises.

Nevertheless, it appeared that some interest would attach to those sensation curves that could be obtained with the available data, even though not referring

to a standard eye, so the curves shown in Fig. 8 were calculated relative to a white-light spectrum. For this purpose the luminosity values in Table II were averaged and, as primaries, the hypothetical colours

$$\text{Red: } 1.015 R - .015 G$$

$$\text{Green } -.900 R + 2.000 G - .100 B$$

$$\text{Blue: } -.050 G + 1.050 B,$$

expressed in the co-ordinates of Fig. 7, were used. These gave an all-positive set of coefficients for the spectral colours. The actual shape of the sensation curves depends on the choice of the primaries; for instance, the rise in the red curve at the violet end of the spectrum can be removed by a modification in the selection.

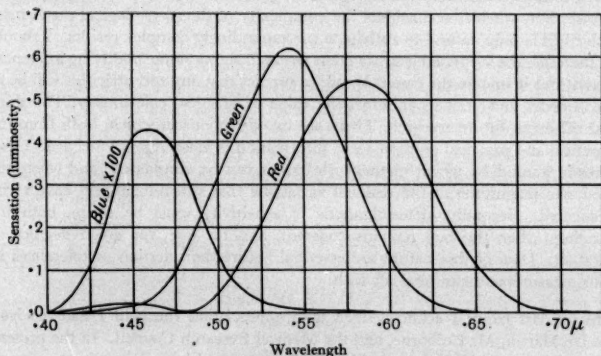


Fig. 8. Sensation (luminosity) curves for white-light spectrum (arbitrary sensation primaries)

Two further series of experiments, subsidiary to the main work, were carried out. The first consisted in testing the value of an illuminated surround in the field of view, by making twenty matches in succession, both with and without the surround, and then comparing the deviations of the readings in the two cases. Several sets of results were obtained, but these were inconclusive. However, as the accuracy of repetition was high in both cases, the mechanical manipulation of the wedges introduced a source of error of the same order as the differences that were being measured. As yet, therefore, no decision for or against a surround can be given. Another experiment which was made consisted in reducing the intensity of both halves of the field equally by means of a rotating sector until the match no longer held. Care was, of course, taken to ensure that the failure of a match was not the result of errors in the sector. Such might have occurred had the aperture become very small. The result of these experiments was to show that

matches held over a very wide range and did not, in fact, begin to fail until the illumination had been decreased to about 1 or $\frac{1}{2}$ photon. The intensity at which colour matches were made in the ordinary work varied enormously, but an average estimate would give a value of about 250 photons.

There are three points, I think, which may well be emphasised in concluding this paper. First, it has become abundantly clear that, until data for a "normal" eye have become standardised, the scope of colorimetric science will be strictly limited. This applies to all forms of colorimetry and not merely to the trichromatic system. The second point that needs to be made is in the nature of a caution. The experimental facts that have been given and the discussion of the theory in general give the impression that colorimetry is an exact science following simple mathematical and physical laws. So far as can be judged at present this appears to be the case, but, when one considers the complexity of the physiological mechanism involved, it is only natural to anticipate correspondingly complex results. I should not, therefore, be surprised if subsequent research shows some modifying influences to exist; but if such is the case it is safe to predict that any eccentricities will be of a small order and unlikely to affect the value of practical colorimetry. The third point relates to future research. There are two directions in which, both from the theoretical and practical point of view, information is most urgently needed. First, a filter is wanted by which pigment variations can be eliminated; and when obtained, the magnitude of the residual variations that still remain will have to be investigated. Secondly, determinations of sensitivity must be made, both for saturation, when the hue remains constant, and for hue, for given degrees of saturation. Data of this nature are essential before the question of tolerances in colour measurement can be dealt with.

In my last paper I acknowledged with appreciation the help I had received from Dr Martin, Mr Colborne, and the Medical Research Council. In the present instance I have to add the name of Mr M. E. Sions, as his assistance in the experimental and observational work has been of great value and his enthusiasm in the search for recruits to make observations, a rather thankless task, was most gratifying. I have also to tender my very best thanks to all those who provided the observations, especially to those who spent several hours making a complete set of observations through the spectrum.

APPENDIX

During the discussion of the paper it was pointed out by Mr Guild that the standard white specified by the National Physical Laboratory did not, as stated, provide a source with a colour-temperature of 5000° K., but one with a colour-temperature more nearly 4800° K. To avoid confusion, the complete specification is given in this appendix.

The illuminant used is a gas-filled lamp, operated under specified conditions, used in conjunction with a filter consisting of two layers, each 1 centimetre thick, of selectively absorbent liquids. A subsidiary filter of the same type, but of different concentrations of the constituents, is employed in the process of rating the gas-filled lamps. This subsidiary filter is placed between a vacuum lamp, operated at a colour-temperature of 2360°K. , and a Lummer-Brodhun photometer. On the other side of the photometer is placed the gas-filled lamp and the latter is adjusted in voltage until a colour-match is obtained in the photometer. In this way the gas-filled lamp is rated to a definite colour-temperature, although the actual value of this temperature does not appear in the specification. This procedure has been considered best owing to the uncertainties at present existing as to the temperature scale above 2500°K. The colour-temperature actually obtained in this way is at present believed to be very close to 2900°K.

The lamp, as thus rated, is used in conjunction with the "white light" filter, to provide a standard illuminant for coloured materials and a standard "white" for unit evaluation. The energy distribution departs appreciably from that of a black body, but the integral colour matches that of a black body at a temperature of approximately 4800°K. A colour-temperature of 5000°K. was originally aimed at, but after the filter had been developed it was found necessary to reduce the working temperature of the gas-filled lamp from that first contemplated, owing to rapidity of ageing.

The filters used have the following specification: Each filter consists of two solutions *A* and *B* contained in colourless glass cells having two compartments each 1.000 cm. thick.

White light filter

Solution <i>A</i> :	Cupric sulphate	2.30 gm.
	Ammonia (density .90)	230 cc.
	Distilled water to	1000 cc.
Solution <i>B</i> :	Cupric sulphate	15.0 gm.
	Cobalt sulphate	15.0 gm.
	Distilled water to	1000 cc.

Auxiliary filter for rating lamps

Solution <i>A</i> :	Cupric sulphate	1.41 gm.
	Ammonia (density .90)	141 cc.
	Distilled water to	1000 cc.
Solution <i>B</i> :	Cupric sulphate	11.0 gm.
	Cobalt sulphate	8.5 gm.
	Distilled water to	1000 cc.

Full particulars as to the making up, storing, and use of these filters are contained in the "Instructions for Use and Maintenance of the Guild Trichromatic Colorimeter, H. 93" issued by Messrs Adam Hilger, Ltd.

DISCUSSION

Mr J. Guild (partly communicated): I think Mr Wright is to be congratulated on an exceedingly valuable contribution to the subject of colour vision and colorimetrics. His conclusion that the evaluation of the primaries from two colour matches with monochromatic light instead of, as is usual, from a single match with white gives results in which the differences encountered between different observers are very much diminished, although not completely removed, is in accordance with our experience at the National Physical Laboratory. When Sinden's paper on complementary colours first suggested the possibility that the major differences between "ordinary" observers were due to variations in the colouring of the macula affecting the energy distribution reaching the sensitive elements, in the case of stimuli spread over the spectrum, and not to any large extent to variations in the response curves of the sensations themselves, I was attracted by the possibility of using the method of evaluation of units, which Mr Wright has employed, for general colorimetric purposes. The practical disadvantages, for general colorimetry, outweigh the advantages however. The method requires that two standard monochromatic radiations of suitable wavelength shall be readily available in any laboratory in which colorimetry is being done. Further, the evaluation of the units involves two measurements in each of which desaturation of the test field is required instead of a single match involving positive quantities of all three primaries. While these disadvantages are relatively insignificant in a research laboratory they involve a serious complication of routine technique for general colorimetric work. I concluded therefore, as Mr Wright also concludes, that the traditional method of evaluation of units from a white match is preferable for general purposes.

In this connection it may be well to point out that the white used by Mr Wright, which is the National Physical Laboratory standard white, is not correctly described as having an energy distribution similar to that of a black body at 5000°K .*

Of the results obtained by Mr Wright in this work, one of the most interesting and significant is the distribution of the "white" points in Fig. 6. It is difficult to see any way of avoiding his conclusion that this proves the major differences to be due to various degrees of macular pigmentation. There would, of course, be no reason for even trying to avoid this conclusion but for the fact that many physiologists fail to find any appreciable pigmentation in the living eye, and hold that the development of the yellow spot is a post-mortem effect. Mr Wright's result certainly adds a very weighty contribution to the circumstantial evidence, already considerable, in favour of the existence of pigmentation in the living eye even though this may be much more pronounced after death.

Most of the incidental results of this work, relating to the technique of colour matching, are in agreement with our experience at the National Physical Laboratory. In particular may be noted the fact, very important from the practical point of view, that the match, with the field size used, is not dependent on field brightness. I have verified this point carefully on many occasions, and if precautions are taken

* See Appendix, p. 158.

to eliminate misleading effects which may arise at very low or very high illuminations due to the large tolerances which exist under those conditions, it can be demonstrated that the match is quite independent of field brightness.

The only point of technique on which I disagree with Mr Wright is when he advises disturbing only one primary at a time when repeating observations. There is a great temptation to do this and in nine cases out of ten it may make no difference to the result. We have found, however, that the possibility of obtaining a systematic error running through the whole of a series of observations is greater if the plan is adopted than if all three primaries are disturbed before each matching.

Mr Wright is not himself satisfied with the luminosity measurements in this paper. It is very difficult indeed to obtain these constants by flicker photometer measurements, owing to the difficulty of obtaining the necessary high field brightness. With the big colour differences involved in comparing the primaries the results are very sensitive to departures from the standard field brightness.

The best procedure, in my opinion, is to obtain three filters, red, green, and blue, and calculate from their spectrophotometric curves and the visibility curve their relative transmission for light from a specified source. Then if these filters are successively matched in the colorimeter, using the source in question, the luminosity coefficients of the primaries can be calculated from the readings. This process requires the visibility curve to be known for each observer if the object of the work is to analyse the properties of individual observers. On the other hand, if the object is to work out the mixture curves for the mean of a number of observers, one may take the standard visibility curve as applying to them. By this method, applying the standard visibility data to the mean of the colour match data for seven observers, we have obtained a very consistent set of mixture curves which we employ provisionally at the Laboratory pending the extension of the work to a larger group.

There is only one point of criticism with regard to the presentation of the results which I wish to offer. I wish Mr Wright had given his final results (Table I) in terms of the primaries red ($\cdot70\mu$), green ($\cdot5465\mu$), and blue ($\cdot436\mu$). As he points out, data given for any set of primaries can be converted to any other, but the conversion takes a little time, and it would facilitate comparison of results if each worker converted his own data to a common basis.

Now the primaries I have mentioned are quite as arbitrary as those used by Mr Wright. The point about them is, however, that they have for some time been adopted as standards for colorimetric purposes by the National Physical Laboratory, because of the practical convenience in standardising colorimeters without the aid of spectroscopic apparatus. They are the only set of primaries which has as yet been put forward for such purposes, and are in use by various colorimetrists in industrial laboratories.

Prof. L. C. Martin: May I express my congratulations and thanks to Mr Wright? It is clearly important that the physical specification of the standard white should be added to the paper. It would be helpful if we could obtain not only the relevant

details of the method of standardisation by the National Physical Laboratory but also the transmission data of the filters and some approximation to the energy distribution.

It has been a great pleasure to watch the progress of Mr Wright's work, which has given our resumption of research in colour vision a valuable start. It seems to me that the great value of Mr Wright's work lies in the way in which he distinguishes between colour vision variations due merely to differences in macular pigmentation and those due apparently to some differences in the receptor processes. These results are of the greatest importance both practically and theoretically.

How far is it possible to train observers to make extra-foveal matches? It has seemed to me that valuable evidence might be obtained regarding the theories in the paper if the results of such tests could be made sufficiently reliable.

Apparently only a limited class of observers can hope to correct their colour vision by the use of filters, and the hope of standardising a "normal eye" is not so bright as formerly seemed to be the case.

Dr R. J. Lythgoe (communicated): Mr Wright's research is unquestionably the most thorough which has yet been undertaken in this subject. With his complete mastery of the physical side of the problem he has combined physiological sympathies; a combination of qualities which is rare and the absence of which has invalidated an enormous amount of well-meaning work. Mr Wright can express quantitatively the variation in macular pigmentation amongst his observers. Has he ever considered that this pigment may vary in amount in different regions of one and the same retina? This suggestion is not an idle speculation. It was found by Cobb that the difference threshold (Fechner's fraction) may be twice as great for one half of the test-field as for the other. It has also been pointed out to me repeatedly that workers using a Bausch and Lomb colorimeter quite often give wildly different readings for the position of equality of the two fields. Since this is particularly noticeable when using blue dyes, it seems likely that the explanation is to be found in regional variations of the macular pigment. It would be interesting to know whether Mr Wright's results would be influenced by reversing his fields. Selective absorption of light is known to occur not only at the fovea but also in the lens, especially in elderly people. Some factor such as this might account for the fact that the "white" points do not lie on a straight line and would obviate the necessity of assuming that the macular pigment varies in dominant hue as well as in saturation. Finally I should like to criticise the practice of taking readings with a partially dark-adapted eye. There is no condition in physiological optics more variable and more difficult to define than the degree of dark-adaptation. In view of the amount of work which has been done by Cobb, Ives, and Martin on the effects of light surrounds, it is a pity that Mr Wright did not always use a controlled light-surround rather than an uncontrollable condition of dark-adaptation. It is also known, empirically, that readings with the dark-adapted eye are subjectively more difficult.

Mr Wright: I must thank Mr Guild, Prof. Martin, and Dr Lythgoe for their kind appreciation of my work. It is gratifying to find that Mr Guild is able to confirm, from work carried out at the National Physical Laboratory, most of the points that have been brought out in the paper.

So far as the actual existence of the yellow pigmentation is concerned, my own experience leaves little room for doubt on the point. Cases occur in which the colouring is very faint or sometimes, apparently, absent altogether and this may go some way to explaining the fact that some physiologists fail to find any appreciable pigmentation in the living eye.

I note that Mr Guild disagrees with the method of repeating observations by disturbing one drum at a time. I cannot see adequate theoretical grounds why the results should be biased (the amount would, in any case, be very small), but I concluded that, as the matching would be simplified, the observer was less likely to be fatigued and his sensitivity would accordingly be greater. This, I expected, would more than outweigh any systematic error, if such existed, but I made no actual tests. In view, however, of Mr Guild's experiments this conclusion is apparently not correct. It may nevertheless be found, when the question of tolerances has been investigated, that the simpler method will satisfy the demands made in colour measurement.

It is interesting to see that it has been found possible to obtain a consistent set of mixture curves by using the mean data of seven observers. I take it that the observers have been selected to have a mean luminosity curve very similar to the standard curve and to give an average "white" point close to the average of a large number of "white" points. The difficulty in making such a selection is the difficulty I anticipated in obtaining a standard set of sensation curves, but it is, evidently, not insuperable.

As I was unaware of the primaries which the National Physical Laboratory had adopted as standard, I was perforce unable to express my results in terms of them. I can quite realise the practical advantages of using readily available spectral lines as primaries, but on the other hand there would be some advantages in the use of spectral primaries which could be actually embodied in a colorimeter. It is unfortunate that the mercury lamp does not possess any bright red line, as in that case an ideal colorimeter could be designed using the lamp as the source. As it is, with ordinary sources, 436μ is rather far down the spectrum to give sufficient intensity for its satisfactory use as a primary in a colorimeter and, further, 5465μ being somewhat towards the yellow-green makes the area of the colour field lying outside the colour triangle rather bigger than could be desired. It is a difficult point to decide which is the better compromise; personally I should like to see standardised three primaries which could, if desired, be actually used as primaries in a colorimeter, in which case no arithmetical transformations would be necessary.

As an appendix on the specification of the standard white has been added to the paper, there is no call for any further comment here.

In reply to Prof. Martin, extra-foveal matches certainly seem likely to afford valuable results. Those observations that were made in this way were hardly

accurate or extensive enough to give in the paper. With practice it should be possible to obtain results of greater accuracy and some observers, notably those with large amounts of pigment, found the blue primary more sensitive in the extra-foveal than in the foveal region.

Dr Lythgoe's criticisms have to be faced, but they have mostly, I think, been investigated during the work. That the pigment might vary in amount in different parts of the fovea was realised and at least two cases were encountered in which the field did not appear uniform all over, due to this cause. The results in a particular case might be affected slightly by reversing the fields, but the results of a number of observers are hardly likely to be affected systematically.

The fact that the points lie off the line does not appear to be due to variations in the hue of other absorbing media, such as the crystalline lens, as in this case the points would lie in a parallel band and not in a cone.

The problems of adaptation and a light surround were not investigated extensively, but in no case was the state of adaptation or the surround found to affect the matches. Bearing in mind that all the observing was done at the fovea this result is not surprising, and to my mind the only effect that one could reasonably expect would be a modification in the accuracy of the settings or, in other words, an increase in the sensitivity. This may eventually prove to be the case, but the colorimeter used was not sufficiently delicate to indicate the changes. My personal opinion is that a surround field is not practicable in colorimetry. The intensity of the matching field varies so greatly from one match to another, that what would be just the right intensity for one match would be altogether too bright for another. And I think that to regulate the surround intensity according to the field intensity would defeat the end in view, namely, the definite control of observing conditions.

In conclusion I have to apologise for making an error in the paper which is not, I hope, of fundamental importance. It concerns the luminosity measurements and the sensation curves that were derived from them. By a mistake on my part the curves obtained were not, in effect, derived from the mean results of Table II, but the result is really of little consequence as the figures which were used are likely to be as near the true luminosity data as those obtained by experiment. In neither case could the curves be regarded as standard; they were given to indicate the general type of result to be expected.

ON THE TESTING OF A NOVEL PHOTOGRAPHIC SHUTTER

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ABSTRACT. The paper describes the methods which were adopted at the National Physical Laboratory for measuring the durations of exposure and the efficiencies of a "Louvre" photographic shutter, which was recently submitted for test.

INTRODUCTION

In aerial photography the convenience of having the shutter mounted as a separate unit has led to the wide use of focal-plane shutters. With these shutters different parts of the photographic plate or film are exposed in succession, and as the camera is moving at a high speed relatively to the ground, considerable distortion may be present in the image. For this and other reasons consideration has been given to the feasibility of other types of shutter for aerial photography, and recently a new type has been tried. An experimental model was submitted to the National Physical Laboratory for test and it was at once obvious that the ordinary methods* of measuring speed and efficiency could not be applied directly to this shutter. As the procedure adopted in carrying out the test is in some respects novel, it is thought that a description of the methods used may be of interest to members of the Society.

DESCRIPTION OF SHUTTER

A photograph of the shutter in question, which is called a "Louvre" shutter and was made by the Williamson Manufacturing Co., Ltd. for the patentee, Mr H. B. Stringer, of the Royal Aircraft Establishment, Farnborough, is shown in Fig. 1. It consists essentially of a number of thin narrow metal leaves L carried by pinions P which engage with two pairs of racks R , one fixed to the frame F of the shutter and the other to a slide S . To make an exposure this slide is rapidly displaced in a direction parallel to its length by springs sp which are brought into action on pressing the trigger T . The relative motion of the racks causes both a rotation of the leaves through nearly 180° and a translation. The former enables light to pass between the leaves and the latter tends to secure greater uniformity in the exposure

* See J. S. Anderson, *Dict. App. Phys.* 4 (670); *Trans. Opt. Soc.* 22 1920-1 (161); *Proc. Intern. Congress of Phot.* 1928 (302).

given to different parts of the plate. For the next exposure the slide, and consequently the leaves, move in the reverse direction, resuming their original position.

The movement of the leaves can be readily understood from a study of Figs. 2* and 3, the latter of which shows in section the positions of two adjacent leaves

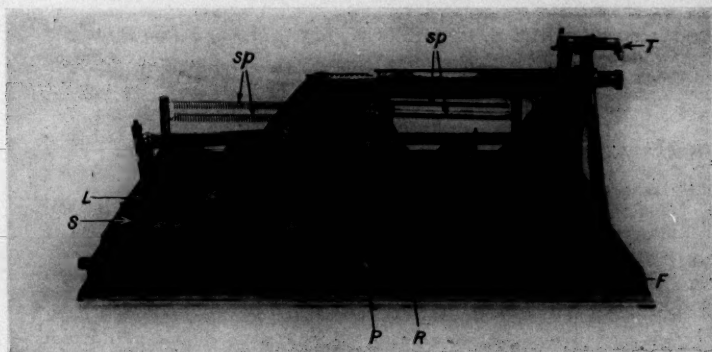


Fig. 1. Photograph of shutter

L, L' for different angles of rotation about the centres C, C' of their pinions. These angles are designated by suffixes, the closed positions being represented by o and 180 . The motion of the leaves is therefore somewhat similar to the action of a Venetian blind, which can be moved from one closed position to another through positions which permit varying amounts of light to pass between the leaves. The shutter leaves have longitudinal grooves to enable them to fit close together in their stationary positions so that no light can pass between them.

The shutter was submitted as a separate unit for use in an aerial camera at a position nearly half-way between the back surface of the lens and the photographic plate, the plane through the centres of rotation of the leaves being normal to the lens axis. The orientation of the shutter was such that the plate would be above and the lens below the diagram shown in Fig. 3. As the leaves move from the position o to the position 180 light transmitted by the lens first of all falls on

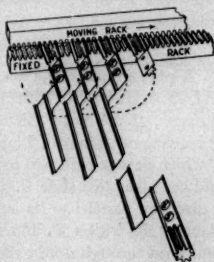


Fig. 2. Louvre shutter

* Fig. 2 is a reproduction of Fig. 7 from a paper by H. B. Stringer, entitled "Air Photography Apparatus," *Proc. Opt. Conv.* 2 1926 (729).

the left side of the plate; as the leaves open more fully light reaches the whole of the plate; finally, as the leaves close again light only reaches the right side of the plate. Thus there is a progressive exposure of the plate. During the whole exposure there are of course always some portions of the plate screened by the shadows of the leaves.

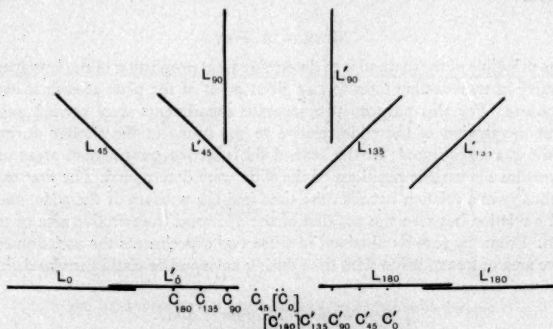


Fig. 3. Diagram illustrating motion of leaves

REQUIREMENTS OF TEST

The three chief factors to be determined in the performance of a shutter are the total time during which light falls on the plate or on any part of it, the duration of exposure at any given point of the plate, and the efficiency at any given point. The first two are definite quantities and susceptible of direct measurement. The definition of efficiency, on the other hand, has to be fixed for each type of shutter. For the shutter under consideration the efficiency at any point of the plate was taken as the amount of light which reaches that point in the actual exposure, expressed as a fraction of the amount of light which would reach it in the period over which the exposure at the point extends if no light were obstructed by the shutter. This particular definition of efficiency was adopted as it was considered the most suitable one for the particular use to which the shutter is put. Theoretically the definition adopted involves the properties of the lens which is used with the shutter, but under actual conditions of use the influence of the precise type of lens used is not important.

In testing such a shutter for speed and efficiency it is of course essential to keep as closely as possible to the conditions under which the shutter is to be used in actual practice. It was necessary, therefore, in measuring the speed and efficiency at any point of the plate to retain the same relative positions and orientations of lens aperture, shutter, and focal plane.

As the efficiency of any shutter is essentially the ratio of two quantities of light the use of photo-electric methods of measuring these has been considered and will probably be adopted at some convenient time. If apparatus of this kind had been standing it would have been employed in testing this particular shutter. In its absence it became necessary to adopt a special method which will now be described.

METHOD OF TEST

The principle of the method is to determine what proportion of the lens aperture is effective in transmitting light to any given point of the plate at each instant of an exposure. For this purpose two separate experiments were carried out. In the first the motion of the slide relative to the frame of the shutter during an exposure was investigated; in the second the effective transmission areas of the lens aperture for various positions of the slide were determined. The first experiment thus gave a relation between the time and the position of the slide, and the second a relation between the position of the slide and the effective area of transmission. From the records obtained in these two experiments the variation of the effective area of transmission with time during an exposure could then be deduced.

Determination of Motion of Slide

The arrangement of apparatus for the first experiment is shown diagrammatically in Fig. 4. A lens L_1 was attached to the slide S of the shutter so that it projected beyond the frame, with its axis perpendicular to the direction of motion of the slide, the frame being held rigidly in a clamp. Light from a "Pointolite" lamp P , concentrated by means of a lens L_2 on a small pinhole in a screen A , was subsequently focussed by the lens L_1 at a point B on the surface of a drum D , the axis of which was set parallel to the direction of motion of the slide. On the release of the shutter the lens L_1 was carried with the slide to the position L'_1 and the image of the pinhole consequently moved to B' . Light from P , after reflection at the mirror M executing 1000 vibrations per second, was focussed on the surface of the drum at C by the lens L_2 . During the exposure the drum, carrying a photographic film, was kept rapidly rotating. In this way a record such as that shown diagrammatically in Fig. 5 was obtained. The curve BB' represents the trace formed by the image of the pinhole and the wavy line C the time trace, the distances between consecutive crests corresponding to $1/1000$ second. The lens L_1 (Fig. 4) being approximately half-way between the pinhole and the surface of the drum, the total distance traversed by the image of the pinhole, measured in a direction parallel to the axis of the drum, is approximately double the distance through which the slide has moved.

The position of the slide at any instant during the exposure can be read from the curve BB' (Fig. 5). Assuming the rotational motion of the drum to have been uniform (this being indicated by equality of the distances between successive crests of the trace C), the portion DD' of the curve BB' would be straight if the velocity

of the slide were uniform. A trace of the form shown in the figure clearly indicates that the slide takes some time to acquire a speed not far short of its maximum value, but subsequently its velocity is approximately constant during the greater part of the motion. It should be noted that the slide moves a certain distance from its first stationary position before light from the lens can pass between the shutter

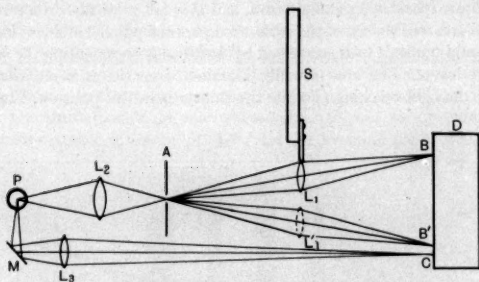


Fig. 4. Arrangement of apparatus for determining motion of slide

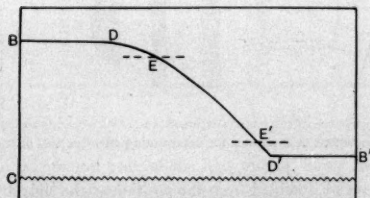


Fig. 5. Diagrammatic record of motion of slide

leaves and reach any point of the plate. Similarly no light can reach the plate when the slide is a certain distance from its second stationary position. The photographically effective portion of the curve is limited in Fig. 5 by the short dotted lines at E and E' and it will be noted from the small change in the slope of the curve between E and E' that the motion is approximately uniform.

Determination of Effective Area of Transmission

The second experiment was arranged to give, for each of a number of points on the plate, records of the effective parts of the lens aperture for various positions

of the slide. In Fig. 6 M represents a micrometer arranged to read the position of the slide S relatively to its frame. In the focal plane of the camera a brass plate P is placed in which are pierced a number of fine holes H , each representing a point of the plate for which the shutter performance is required. If now a small lamp is held behind one of the holes H , light transmitted through the hole will reach the lens L except where it is obstructed by the shutter leaves. This light will emerge into the object space as a parallel beam, and if it fall normally on a screen A the illuminated area will consist of the cross-section of the parallel incident beam which the lens would transmit to H , traversed by dark bands representing the shadows of the shutter leaves. The area actually illuminated serves as a sufficiently exact measure of the light reaching H while the shutter is in this position. The duration

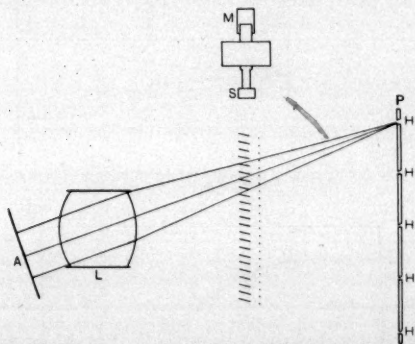


Fig. 6. Arrangement of apparatus for determining effective area of transmission

of exposure at H can be obtained from the position of the slide at which light first begins to illuminate the screen A and that at which it is just cut off, making use of the record of Fig. 5. An ideal shutter would, for the whole of this interval of time, transmit light to H at a rate measured by the illuminated area on the screen after the shutter had been removed from the camera. The real shutter at any instant transmits at the slower rate represented by the reduced area free from the shadows of the leaves. By integration with respect to the time a measure of the radiant energy transmitted to H is obtained, and its ratio to that of the corresponding measure for the ideal shutter is the efficiency.

As the integration involved could not be performed instrumentally, a somewhat different arrangement was preferred. It will be observed that, as we are only concerned with the ratio of areas in the same plane, we may place our screen (in practice a sheet of bromide paper) perpendicular to the axis of the lens in the object space—say in contact with the front of the lens mount. It is now but a small step to bring

the paper to the other side of the lens in contact with the back of the lens mount. We now obtain the shadows of those leaves of the shutter which are not yet effective in addition to those previously recorded, and can trace their movements beyond the limitations of the lens aperture. This is a matter of some importance if considerable accuracy is required when reliance has necessarily to be placed on sampling instead of on complete records. As the record now contains no outline of the effective part of the lens aperture, some other means of marking reference points on the bromide paper must be adopted. Since we are now taking these records on the shutter side of the lens, it is not necessary to make the exposures in the camera. In the actual test it would not have been easy to control the shutter in the way desired while it was in the camera, so that convenience and accuracy for once pointed in the same direction. The shutter, with the micrometer attached, was set up parallel to and at the correct distance from the plate *P*, and the bromide paper was placed in

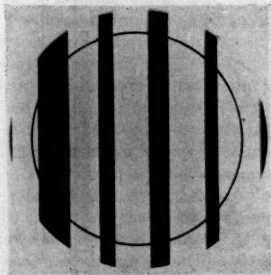


Fig. 7. Record showing areas of transmission for a particular setting of slide

a plane corresponding to the back of the lens mount, being held against a plate containing a circular hole concentric with and considerably larger than the aperture of the lens. The position of the effective aperture of the lens for each of the points *H* relative to that of the circular hole was determined subsequently.

The procedure adopted with the present shutter was to make a series of exposures on bromide paper for different positions of the micrometer, that is, for different degrees of opening of the shutter leaves, for each of the holes *H*. The type of record obtained is shown in Fig. 7. The black portions represent the parts of the aperture which receive light from the hole in question, the bright portions being the shadows cast by the leaves. A black circle has been drawn on the record to show the position and size of the section in the plane of the bromide paper of the cone of light converging to the principal focus of the lens. The ratio of the sum of the black areas within this circle to the total area of the circle gives the fraction of the lens aperture through which light can reach the centre of the photographic plate in the camera for the given position of the shutter slide.

ANALYSIS OF RECORDS

The determination of this ratio for each record can be carried out in various ways; the method adopted will now be described. For the sake of simplicity let us consider the records obtained when using the central hole, the effective aperture of the lens for these records being circular. If we plot the distances of the shadows of the leaf edges from the centre of the aperture for the positions of the slide at which the records were made, we obtain a number of groups of points which when

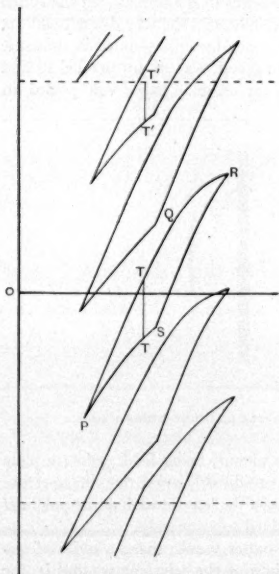


Fig. 8. Diagrammatic record giving positions of shadows cast by edges of leaves

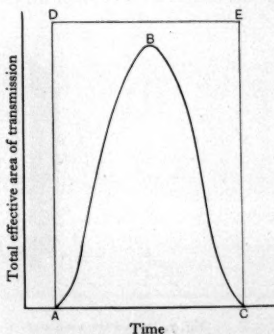


Fig. 9. Diagram showing total effective area of transmission throughout an exposure

joined up give a diagram such as is shown in Fig. 8. The abscissae are the distances traversed by the slide and the ordinates are the distances from the centre of the aperture to the edges of the shadows cast by the leaves. The centre of the aperture is indicated by the horizontal line through *O* and the limits of the effective aperture by the horizontal dotted lines. Each loop represents the motion of the effective edges of one pair of adjacent leaves. Let us consider one of these loops *PQRS*.

The points P, R represent the two positions of the slide at which light can just not pass between the two leaves in question. The portions PQ and SR represent the movement of the outer edges of these leaves and the portions QR and PS the movement of the inner edges*. The vertical distance TT between points on PQR and PSR gives the distance between the shadows of the leaves. Where a loop is intersected by either of the dotted lines, the effective distance between the shadows is of course given by the vertical distance to the dotted line, as indicated by TT' .

The next step in the procedure is to draw on graph paper a circle of the same size as the effective aperture of the lens (or to any desired scale) and to determine the areas between the diameter parallel to the edges of the leaf shadows and the various parallel lines on the graph paper. It was found convenient, for example, to draw the circle on inch graph paper divided into twentieths and to determine the areas bounded by the circle and the parallel lines for each twentieth-inch variation along the axis of abscissae by counting the number of small squares and portions of squares in the areas. The values thus obtained were tabulated and could be used for determining the effective area of transmission between any two adjacent leaves for any position of the shutter slide.

The speed and efficiency of the shutter for the central point of the photographic plate can then be deduced in either of two ways. The first method is as follows. From the loops shown in Fig. 8 the coordinates of the shadow edges of the leaves relative to the centre of the aperture for various positions of the slide are read off and the effective areas of transmission are then obtained from the table by subtracting the appropriate values in pairs. Thus the total effective area through which light is transmitted can be obtained for the various positions of the slide. The values of this area are next plotted against the instants of time during an exposure which correspond with these positions, making use of the curve in Fig. 5. In this way a curve such as is shown in Fig. 9 is obtained in which time is plotted horizontally and total effective area of transmission vertically, the shape of the curve as shown being quite diagrammatic. The points A, C represent respectively the instants at which the shutter opens and closes with respect to the centre of the photographic plate. Thus AC is the total duration of exposure, that is the speed of the shutter, for the centre of the plate. If a rectangle $ADEC$ is constructed so that AD represents the effective aperture of the lens as seen from the centre of the plate with the shutter removed, the efficiency of the shutter for this point, according to the definition we have adopted, is given by the ratio of the area ABC to the area $ADEC$.

The alternative method of deducing the efficiency is an arithmetical one and gives the result to about the same degree of accuracy; it probably takes less time than the one just described. The procedure is as follows: The displacement of the slide during an exposure is divided into a convenient number of equal intervals and the corresponding time intervals $t_1, t_2, t_3, \dots$ are found from the curve of Fig. 5. The mean position of the slide for each of these intervals is then determined from the loops of Fig. 8, account being taken of the shapes of the effective portions of

* The edge which is nearer the axis of rotation is taken as the inner edge of the leaf.

these loops in these intervals. The effective areas of transmission $A_1, A_2, A_3, \dots$ are next obtained from the table of areas by subtraction in pairs and subsequent summation. The equivalent area of transmission during the whole exposure is then given by

$$A = \frac{A_1 t_1 + A_2 t_2 + A_3 t_3 + \dots}{t_1 + t_2 + t_3 + \dots}$$

It is obvious that this area A corresponds to the area ABC in Fig. 9, the procedure adopted in this instance being equivalent to an approximate summation of the area ABC . The results obtained in this way proved to be correct to about one part in a thousand. The efficiency is of course given by the ratio of A to the area of the rectangle corresponding to $ADEC$ in Fig. 9.

The whole procedure is then repeated with the shadow records obtained with the other points H (Fig. 6). The effective aperture of the lens with respect to each of these points is of course not circular, but the method of analysis is similar to

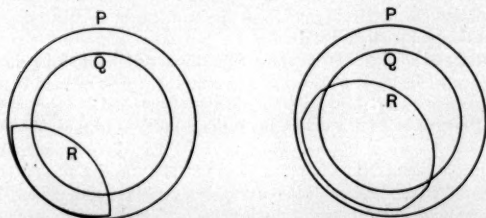


Fig. 10. Diagrams showing effective apertures of lens for oblique points

that described above for the records obtained with the central point. The actual shape of the effective aperture and its position relative to the effective aperture for the central point can be found in the following way. The lens is placed in the camera and a "Pointolite" lamp mounted at a considerable distance away so that its image in the focal plane coincides with one of the points H . A piece of bromide paper is then held against the back of the lens mount and a suitable exposure made. Keeping the paper in the same position, a short exposure is next given to the light from another "Pointolite" lamp placed at a distant point on the axis of the lens. The procedure is repeated for the other points H . The records thus obtained resemble those shown in Fig. 10. P is the full aperture of the lens (the image being formed by stray light in the room), Q is the effective aperture for the central point H (Fig. 6), and R is the effective aperture for the oblique points concerned.

In analysing the shadow records obtained with each of the oblique points the effective aperture is first of all traced in its correct position on the records. Then a straight line is drawn through any suitable point of the aperture parallel to the edges of the shadows and this is taken as the reference line from which the co-ordinates of the edges are measured, and the areas are calculated in the same way

as has already been described for the records obtained with the central point of the photographic plate.

The results obtained with this shutter showed that as long as the leaves are suitably proportioned the variations in the durations of exposure and in the efficiencies at different points of the photographic plate are very small. As is to be expected, the efficiency of the shutter is much lower than that of a focal-plane shutter working with a wide slit. On the other hand this type of shutter possesses one distinct advantage over the focal-plane shutter, namely, that the ratio of the total time during which light falls on the plate or any part of it to the duration of exposure at any point is very much smaller, so that there is less likelihood of distortion in the image.

In conclusion, I have much pleasure in recording my indebtedness to Mr T. Smith for the interest he has taken in this work and for the many valuable suggestions he has made. My thanks are also due to Mr C. M. Williamson for providing the photograph reproduced in Fig. 1, and to my colleague Mr L. C. Cordle for his assistance in carrying out the test and making the many records required.

DISCUSSION

Mr C. M. Williamson: As the manufacturer of the shutter in question I have rather more than a passing interest in the very interesting paper Dr Anderson has just given us on the methods used in testing this shutter.

I little thought, when submitting this shutter, of the amount of work involved in obtaining the desired data and I think the paper proves, if any proof were necessary, the thoroughness with which problems submitted to the National Physical Laboratory are tackled.

The test figures submitted to me in the N.P.L. report are rather disappointing in view of the encouraging results I had previously obtained from the shutter when tested in the air. I do not doubt the accuracy of these figures for one moment, but I notice that Dr Anderson mentions that photo-electric methods might be employed and I should be glad to know whether there is any possibility of such apparatus being available shortly for such a purpose.

Dr Anderson also mentioned that, as the shutter had been fitted mid-way between the lens and the focal plane in the camera sent with the shutter for testing, this position had been retained when carrying out his experiments. So far as I am concerned this position was largely accidental and since the relation between the shutter and focal plane remains constant it would be interesting to know how the efficiency would be affected if the shutter were used with a long-focus lens.

Mr L. B. Booth: The paper just read is of the character which one has come to expect of the staff of the National Physical Laboratory and in particular of Dr Anderson, and I have much appreciated hearing it. I may claim to have a peculiar interest in the subject as I had the first model of this shutter for test in 1926. In the main my results are very similar to those obtained by Dr Anderson. The test for exposure which I used was to pass light through the lens so as to fall

on a slit placed immediately in front of a rotating drum carrying a film and situated at the focal plane: this drum was driven by means of a phonic motor controlled by a tuning-fork at 600 revolutions per minute, so that the length of the trace on the film gave a measure of the duration of exposure. In the tests which I undertook I used a 10-inch $f/4.5$ lens and the shutter was placed in two positions, (1) about 1 inch behind the lens, (2) about $1\frac{1}{2}$ inches from the focal plane. The exposure times were very little different in the two cases.

Distortion was measured by passing the light similarly on two separated slits, small mirrors being placed near them to cause the light to be reflected approximately on to the film. The difference between the slits on the film was first measured by means of a photograph taken with the drum at rest. With the drum in motion two traces, one for each slit, were obtained. The distortion may be measured by the difference between the middle points of the two traces and the "stationary" distance.

The question of efficiency leads me to the consideration of a point which seems not to have been considered hitherto. The usual definition of efficiency is the ratio of certain area integrals. Surely this is only an academic way of dealing with the subject. In photographs, particularly for aerial work, the only matter of importance (excluding of course questions of distortion, etc.) is density of deposit on a sensitive surface and any test of efficiency should be in relation to the result required. If the usual efficiency diagram be drawn, a second curve should be drawn giving the "light-effect" per unit time corresponding to each part of the curve with the illumination actually used for the test and with a plate or film of the character actually used. The inertia of the plate will inevitably affect the result as the darker portions of the subject will not receive any density contribution until the shutter has opened to an appreciable aperture. The shadows will not only be exposed for a shorter time, but will also receive a less amount of light proportionally than the high lights. The same effect is to be noticed in comparing photographs taken with a large and small aperture respectively, with exposures such that the general light effect is the same. The latter always appears to possess the greater brilliancy, generally of the soot and whitewash order. One would therefore expect to find that with an efficient focal-plane shutter the photograph would be better exposed proportionately for the shadows than with a between-lens shutter of poor efficiency even with a proportionately longer exposure. I suggest that our criterion of efficiency ought to be altered and brought into correct relation with actual conditions: for instance, the light-effect produced on some standard plate by some object illuminated in some standard manner.

My tests of the present shutter were conducted on those lines. Photographs of an illuminated circle were taken using a standard focal-plane shutter whose efficiency could be obtained easily by calculation and using the louvre shutter. The slit of the focal-plane shutter was varied until the densities of the two photographs were equal (the comparison was made on a densitometer using a selenium cell). Knowing the speeds of the two shutters, the efficiency is easily calculated. The result with the shutter near the lens was almost identical with that found by

Dr Anderson. With the shutter nearer the focal plane there is a considerable gain in efficiency, but there are more variations both in direction of exposure and in efficiency for various points of the focal plane. If the shutter be too close to the focal plane a series of parallel dark and light bands appears on the photograph showing conclusively the variation in "light-effect." For measurement purposes, say in surveying, this streakiness would probably be of no importance and the increase in efficiency would be a great gain.

In comparing distortion with that of a focal-plane shutter my own tests were made with equal light-effects for the two shutters. I believe that, if allowance be made for this, the advantage as regards distortion of the louvre shutter is not at all so great as appears in Dr Anderson's results, which again are in fairly close agreement with mine.

Captain T. Y. Baker: The criterion as to what constitutes efficiency in a shutter used in air survey photography is difficult to formulate. The photograph is used for map-making and may be looked upon as a record of the angles subtended at the lens by a whole series of points on the ground at the time when the photograph was taken. The subsequent use to which the negative is put involves, in effect, some form of measurement in one of the elaborate plotting machines used in air survey work, with a sensitivity which corresponds to a few thousandths of a millimetre on the negative. If we take 150 feet per sec. as the speed of the aeroplane there will be a distortional displacement between points upon one side and points upon the other side of the plate amounting to 18 inches, on the ground, for each hundredth of a second that a focal-plane shutter takes to traverse the plate. The photograph does not give a true representation of the ground. It shows what the ground would look like if it were stretched in one direction. Where successive pictures have to be used to determine contour lines stereoscopically it is clear that the distortion produced by a focal-plane shutter may assume very serious proportions.

It seems, therefore, that any figure that assesses the efficiency of a shutter for air survey use ought to be based primarily upon absence of distortion. A secondary requirement is that the exposure of different parts of the field shall be such that the various marks on the ground can be recognised and used with sufficient accuracy in the process of measurement. In very general terms the air surveyor can put up with poorer negatives than would be ordinarily considered satisfactory in a photograph for pictorial purposes. The formula upon which the efficiency figure is based ought to take account of these facts, and it should not be beyond the wit of man to produce something which is a rough approximation to what is wanted. The method of testing the louvre shutter that Dr Anderson has described is extremely ingenious and the manner in which he has overcome difficulties is in keeping with the high standards of the National Physical Laboratory, but I am sure he will agree with me that there is something wrong with a formula that assesses at 90 per cent. a focal plane shutter which has distortion, and at 33 per cent. this new type in which the distortion has been practically eliminated, especially as it appears to give pictures that are all the surveyor needs for map-making purposes.

Dr Anderson: In reply to Mr Williamson, it is our intention to experiment with photo-electric methods of shutter testing when time permits. The use of a long-focus lens with the shutter would only have a small effect on the efficiency of the shutter.

It is interesting to learn from Mr Booth that his results, obtained by a quite different method, compare fairly well with mine.

Mr Booth's and Capt. Baker's remarks on the definition of efficiency are of interest. Efficiency in the paper denotes, in accordance with the usual practice, merely the light-transmitting efficiency of the shutter. In assessing efficiency from the standpoint of the quality of the picture obtained, it is obvious, as Mr Booth and Capt. Baker have pointed out, that two other important factors have to be taken into consideration. The first of these is the characteristic property of the photographic plate or film used in the camera. It is clear that the efficiency of exposure will vary with the nature of the plate or film used and with the nature of the illumination of the objects being photographed. The second factor is the distortion produced by the shutter. The question of laying down tolerances for distortion is one which might with advantage be taken up by the Air Survey Committee. It is not, however, within the scope of this paper to discuss in any detail the effects of such factors as have just been mentioned. The main purpose has been to describe the methods used in determining the efficiency of the shutter considered as a unit in itself.

With regard to the comparison of the distortion of the louvre shutter with that of a focal-plane shutter the advantage of the former is not quite so great, as Mr Booth points out, when allowance is made for equal light-effects. In such circumstances the distortion given by the louvre shutter is not exactly eliminated, as Capt. Baker seems to infer. If, however, the light were sufficient to allow of the louvre shutter being used when the total time of exposure at any point of the plate was the same as with a focal-plane shutter, the former would have a most decided advantage over the latter as regards distortion.

Although this shutter is of considerable interest in that it marks a new departure and does possess less distortion than a focal-plane shutter, I think that the solution of the shutter problem for aerial photography will probably be found in other directions.

REVIEWS

The Prescribing of Spectacles. (Third Edition.) By A. S. PERCIVAL, M.A., M.B., B.C. Pp. 239; 29 Figs. (Bristol: John Wright and Sons, Ltd.; London: Simpkin Marshall, Ltd., 1928.) Price 15s. net.

This edition has been re-written and enlarged from 168 pages in the first edition to 239 pages. The book is by a well-known oculist and is addressed rather to the ophthalmic surgeon than to the optician or to the optical students in the Polytechnics.

There are four chapters. The first is introductory and deals mainly with accommodation, with the measurement of the distance of the near point, and with the symptoms and treatment of insufficiency of accommodation. The greater part of this chapter is acknowledged to be due to Duane's paper on subnormal accommodation (*Arch. Opth.* 1925).

Chapter II, on static refraction, is concerned with the refraction of the eye when the accommodation is relaxed. It contains very clear and concise descriptions of the subjective tests of ametropia and visual acuteness including the pinhole test, the chromatic test, and the use of the usual charts. The practice of the fogging system is recommended both for simple ametropia and for astigmatism. "The highest convex (or the weakest concave) glass is given that just enables him to distinguish one set of lines. The strength of this glass is reduced until he can see one of the lines distinctly, while the rest are indistinct, especially those at right angles to the distinct one. The distinct line gives the meridian of *greatest* curvature. Let us suppose it is the line at 80° from the horizontal. On now holding in front of the trial frames concave cylinders, with their plane axes at right angles to the 80° line (i.e. at an angle of 170°), of gradually increasing strength we shall eventually find that cylinder with which the 170° line can be defined. This is the correction."

Dr Percival is of opinion that "no test for astigmatism is reliable without the instillation of a mydriatic, and it is well not to waste too much time on subjective tests, as a more accurate determination can be made in a far shorter time by the objective tests."

He then proceeds to describe the use of the ophthalmoscope and the retinoscope in measuring the ametropia objectively, and the use of the ophthalmometer in measuring the radius of curvature of the cornea in any meridian, and says "as a scientific instrument" the ophthalmometer "is admirable for determining the curvature of the cornea but unfortunately the astigmatism given by the instrument does not give the power of the cylinder required in the correcting spectacles. It merely gives the power of the cylinder which, if placed in contact with the cornea, would correct the anterior corneal astigmatism." Assuming that the glasses will be worn at a distance of 13.6 mm. from the cornea, tables are given for the values of the positive and negative correcting cylinders corresponding with a number of ophthalmometric readings.

A detailed method and order of procedure is then suggested, followed by a valuable statement of the treatment to be adopted or the power of lens to be prescribed in hypermetropia, myopia, astigmatism, anisometropia, and aphakia.

Paragraphs on "Tilting the lens," on bifocal lenses, and on peripheral vision, and a very interesting account of the author's periscopic lenses conclude this chapter of some 60 pages.

Chapter III (60 pages) treats of the "Faulty tendencies and deviations of the ocular muscles." The nomenclature and clinical properties of prisms are first described and then the manifest and the latent deviations of the eye known as squint and heterophoria. The tests known as static tests to determine the positions of the eyes when at rest and dynamic tests which determine the ability of the eyes to move are then gone into very fully and clearly. The treatment of the various phorias is suggested and the range of

convergence and the relation between convergence and accommodation are investigated and illustrated by charts in which metre angles of convergence are plotted as abscissae and the reciprocals of the distances for which the eyes are accommodated as ordinates.

The last chapter of 77 pages deals with theoretical optics and gives the mathematical solutions of most of the optical problems that arise in the preceding chapters. The most interesting part of this chapter is the description of Dr Percival's method of designing periscopic lenses. I notice that he has made a new Fig. 24 which shows the chief ray of the *emergent* oblique pencil passing through the centre of rotation of the eye instead of that of the incident pencil as in Fig. 21 of the first edition.

The essence of the method of design is (1) to vary the curvatures of the two surfaces of the lens, keeping the axial power constant, so as to make the circle of confusion of an oblique pencil focus on the macula, and (2) to make the size of this macular image not larger than the sectional area of a macular cone, the radius of which is 0.001 mm.

The angle which the chief ray of the oblique pencil considered makes with the axis is 30° , the distance of the centre of rotation of the eye from the last vertex of the lens is taken as 27 mm., and the index of refraction as 1.523.

Tables for both positive and negative lenses of various total powers show the powers of the two surfaces of each lens; the "residual" astigmatism in dioptres; the axial thickness of the lens on the assumption that it is 40 mm. in diameter; the radius of the retinal image; and the "eccentric" power of the periscopic lens.

It may be pointed out that it is possible to vary the curvature of the two surfaces of the lens, whilst keeping the axial power constant, and so make the circle of confusion of an oblique pencil focus on the macula when the eye has rotated through say 30° , but in doing so one uses up the only degree of freedom and consequently it is no longer possible to vary the size of the retinal image.

In calculating the size of the retinal image Dr Percival neglects the spherical aberration of the optical system of the eye and merely uses the ordinary Gaussian equation to get the size of the image. As I have pointed out elsewhere, if one wishes to calculate the size of the retinal image to the order of accuracy of 0.001 mm. it is not safe to neglect the spherical aberration, and in my opinion the sizes given in Dr Percival's table cannot be relied on.

On page 190 we have an investigation into "the power of an oblique cylinder" in which the author attempts to show that "in every case the power of a cylinder C set at axis θ has the power $C \sin^2 \theta$ in the horizontal meridian, and $C \cos^2 \theta$ in the vertical meridian." If one uses the word "power" in this passage in the same sense as it is used throughout the book, viz. as the reciprocal of the focal length in metres, the passage is incorrect, since every element of the cylindrical surface acts like every other and has two powers, one equal to C and the other equal to zero.

The book ends with a useful appendix containing various tables of mathematical constants and the various regulations and tests in use for candidates for the Army, Navy, Air Force, Mercantile Marine, and for the Indian Medical, Pilot, Railway, and Marine Services.

A. W.

Forschungen zur Geschichte der Optik. Edited by MORITZ v. ROHR with the assistance of H. BOEGEHOLD, T. H. COURT, F. P. LIESEGANG and A. v. PFLUGK. (Berlin: Julius Springer.)

This is a new journal which will be published from time to time as a supplement to the *Zeitschrift für Instrumentenkunde*. The first number, which was published in December, 1928, contains a paper by Moritz v. Rohr entitled "Eine Erinnerung an Joseph Fraunhofer," and one by H. Boegehold entitled "Der Glas-Wasser-Versuch von Newton und Dollond." The cost of publishing this journal is being defrayed by Messrs Carl Zeiss, Jena.

ABSTRACTS OF PATENT SPECIFICATIONS

281828. Digby, T. J.

OPTICAL ILLUSIONS.

The image of a spectator or object situated in front of a mirror is made to appear in a determined position upon an object arranged behind the mirror. The mirror, which is thinly silvered, is adjustable on trunnions, and carries lamps arranged to direct the light in such a way that the image of the illuminated spot appears in the required position. By this means, for instance, the image of the head of an actual person appears upon the body of a headless dummy placed behind the mirror.

282149. Wheatley, G., and others.

ARTIFICIAL DAYLIGHT.

An electric lamp is mounted within an opaque reflector, the inner surface of which is painted blue. This reflector is formed in two portions, which intersect at a position corresponding to the direction of maximum intensity of light.

282187. Stewart, J. G.

MICROSCOPES.

The instrument comprises a microscope and illuminator for carrying out eye examinations. The illuminator is adjustably hinged to the stand of the instrument, and projects an image of the aperture stop into the centre of the field of the microscope. This slides upon a circular guide, arrangements being made so that it can pass from one side of the illuminator to the other.

282209. Barr and Stroud, Ltd., and others.

STEREOSCOPES.

A folding topographical stereoscope comprises hinged base members carrying stays supporting pairs of mirrors, by means of which photographs may be viewed through suitable sighting apertures. Frames carry grid plates which lie over the photographs, and can be adjusted with respect to each other.

282253. Penrose and Co., Ltd., and another.

DIAPHRAGMS.

In obtaining photographs through a screen, a lens stop is employed having opaque portions, which may be adjustable, corresponding in direction to the lines of the screen. The object is to improve the high lights of the picture.

282255. Patten, J., and another.

VEHICLE LAMPS.

The reflector comprises upper and lower parabolic portions connected by a cylindrical portion, separate sources of light being placed in each half. The sources may be separated by a non-reflecting partition, or one or both bulbs may be silvered upon the side nearer the axis.

282282. Martin, K.

LENSES.

The lens of a projector or signalling lamp is so shaped as to have a flat or channelled base portion, merging into a concave or channelled intermediate portion, the central part being of a highly convex, non-spherical form.

282377*. Jensen, R. O.

PROJECTION SCREENS.

The front of a plate of glass is shaped to form lenticular elements, the foci of which lie upon the back surface. An opaque layer, continuous except at the position of the focal points of the elements, is laid upon the back of the plate.

* Specification published before acceptance.

282422*. Photogrammetrie Ges.

OPTICAL SYSTEMS.

The optical system of a cellular camera for aerial surveying consists of a series of objectives symmetrically arranged and directed to cover a wide area. The light passing through them is then directed by trilateral prisms to lay the image in a common focal-plane, so as to provide a continuous picture without gaps of re-entrant angles.

282674*. Zeiss, C.

LAMPS.

A street lamp is designed to illuminate a rectangular area. The source is enclosed in a barrel-shaped glass body, the longitudinal section of which forms a parabola. The upper half is silvered, the lower half having a clear central portion with diffusing margins.

283203*. Zeiss, C.

PROJECTION APPARATUS.

In apparatus for projecting images on to the clouds, the axis of the fixed part is substantially horizontal. An image of the source is formed by a mirror in the neighbourhood of the objective, the mount of which carries an adjustable reflector. By means of worm gearing the reflector may be moved to produce a circular movement of the image.

283234. Stobie, V.

STEREOSCOPES.

Apparatus for viewing projected stereoscopic pictures comprises two pairs of mirrors or prisms, two or more of which are pivoted, and so connected as to be adjustable simultaneously. In one arrangement mirrors are connected in pairs, operated by right and left-handed screws.

283346. Taylor, E. W.

MEASURING ANGLES.

The graduation lines on a divided circle are tangential to a smaller circle concentric with it. Opposite sides of the circle are projected into a single eyepiece, in which there is a fixed mark to give the coarse reading. The fine reading is obtained by moving one image by a micrometer until the graduations on the two scales coincide.

283358. Holman, A. J.

PROJECTION APPARATUS.

In a kinematograph in which the film is moved continuously, the main condenser of the projecting system is made astigmatic, to throw an elliptical patch of light upon the gate. At this point a cylindrical lens is mounted to render the beam circular at the compensating lenses, where an additional concave lens, of a different kind of glass, is placed to give colour correction. The light then passes through the diaphragm to the projecting lens.

283859*. Voellmy, H.

REFRACTOMETERS.

Two quartz plates contained in a liquid bath are placed face to face, enclosing prismatic grooves, which are filled with the liquid under test. A parallel beam of light is passed through the plates, and then reflected into a spectrograph. Part of the rays passes between the grooves, and serves to provide a comparison with the refracted and dispersed rays which have passed through the liquid in the grooves.

284321. Zeiss, C., and others.

STREET LAMPS.

In an anti-glare lamp, the bulb has a silvered cap, and is placed at the focus of a reflector, which is semi-circular in transverse section, and parabolic or elliptical in longitudinal section. The curved surface is continued by inclined directive or dispersive reflectors.

* Specification published before acceptance.

284607*. Herzfeld-Hoffman, F.

EXAMINING LIQUIDS.

The optical properties of liquids, such as colour, turbidity, rotation of the plane of polarisation, etc., are examined by the use of a container fitted with a stepped transparent plunger of quartz or glass, which enables two columns of different length to be compared.

284746. Robinson, J.

RAY SCREENS.

In order to assimilate the ultra-violet spectrum of a quartz lamp to that of sunlight, a screen of mica or compressed air is employed. The screen may be formed upon or in connection with the bulb itself, which may also be coloured to cut out part of the visible spectrum.

284871. Zeiss, C., and others.

STABILISING APPARATUS.

The axial direction of telescopes, etc., on board ship is maintained constant by means of a separate stabilising apparatus. A gyroscope controls the movements of two tubes, which are communicated to the telescopes by electrical transmitters, one correcting movements in azimuth, the other in altitude.

284995*. Soc. du Film en Couleurs Keller-Dorian.

PROJECTION APPARATUS.

A colour transparency provided on one side with a pattern of minute refracting elements is projected for printing by a system of lenses arranged to direct parallel rays upon the image. The projector lens consists of a double symmetrical system, of which one half forms images of the elements in the plane of the diaphragm, the other half projecting these upon the image-receiving surface.

285094. Jurgens, K.

OPERA GLASSES.

The eyepiece tubes are fitted with racks engaging with pinions upon the ends of a cross rod which is controlled by a central milled head. The pinions, which are preferably of the same diameter as the rod, may be independently adjusted, and then be relatively fixed for simultaneous movement.

285112. Glausen, M., and others.

SURVEYING INSTRUMENTS.

The instrument is secured to an inverted spherical cup resting by its edge upon a concave spherical support. A dependent rod operates a central screw clamp to lock the instrument in its adjusted position.

285367*. Zeiss, C.

PROJECTION APPARATUS.

Transparencies in the form of stencils are mounted upon a carrier which is intermittently rotated to bring the objects successively into the beam of light. The separate transparencies are themselves rotated during projection, so as to produce a moving image upon the clouds.

285519. Harrison, W. M.

LIGHT-SENSITIVE DEVICES.

Motor vehicles are fitted with a box carrying a sensitive cell, upon which light from approaching vehicles is concentrated by a lens. When a certain intensity is reached, the cell energises a relay, which cuts out the main headlights, dips the reflectors, or operates an anti-dazzle screen or other device of the same character.

* Specification published before acceptance.

285738. Television Ltd., and another.

OPTICAL APPARATUS.

Light from each elemental area of an object is employed to form an object, the arrangements being such that rays from the separate elements follow separate paths. A series of parallel, converging, or diverging tubes, bent or curved tubes or rods providing internal reflections, or other means may be employed for the purpose, each tube or rod conveying the light from a separate area.

285848*. Legendre, R. A.

COLORIMETERS.

In a colorimeter in which the optical system provides two sighting lines, the tank system consists of two units, each comprising three containers. In one tank the thickness of liquid remains constant, while in the other two it varies in opposite senses as the tank system is moved across the sighting line. One tank may be rectangular, the others consisting of one erect and one inverted prism.

285891*. Pech, L.

REFLECTORS.

The reflector of a vehicle lamp consists of two sections, the lower one being displaced axially forwards relatively to the upper. Each section comprises two portions, the front portion being of parabolic shape, and so arranged with respect to the light source that all reflected rays take a downward course. The back portion of each half is of circular section, merging into the parabolic portion.

286052. Robertson, J. R.

COLOUR SCREENS.

The component lenses of an anastigmatic system are mounted in a tube which also encloses sealed chambers containing rarefied gases, capable under electrical discharge of giving coloured glows, for instance, red, blue, and green respectively. These discharges are automatically switched on in succession, so that successive photographs may be taken through screens of different colour.

286254*. Kamei, K.

STEREOSCOPY.

The right and left images of stereoscopic pairs are superimposed upon a kinematograph film, the intensity of each image being varied in the opposite sense to that of the other. A filter plate provided with graduated areas is rotated behind the taking lenses, or in the beams reflected from a pair of mirrors arranged to provide stereoscopic view points.

286265*. Zeiss, C.

REFLECTORS.

A reflector fitted to an overhead lamp takes the form of a concave surface of revolution, the generating curve being such that all reflected rays cross the axis between two fixed points. The object is to provide an intense but shadowless field of illumination above an operating-table.

286394. Adcock, F.

ANTI-DAZZLE DEVICES.

All light emitted by lamps within a predetermined region is plane polarised in a given direction, and observation is made through analysers suitably orientated. The directions of the planes of polarisation and analysis are defined in relation to the direction of the beams, and not to the position of vehicles.

286524. Kurita, T.

LEVELS.

To maintain constant the size of the bubble, the level is provided with an expansion chamber consisting of an air tube fitted with a spring plunger, rendered tight by a mercury packing.

R. J. T.

* Specification published before acceptance.